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INTERMEDIATE PULSEWIDTH
LASER SYSTEM

Final Report

August 1965 - 30 December 1970



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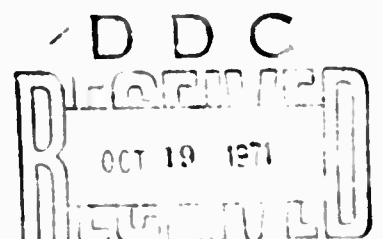
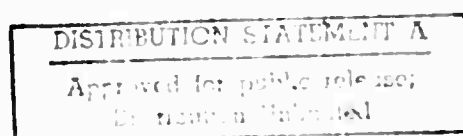
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Electro-optical Modulators						
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ABSTRACT

This report delineates efforts expended in the design and construction of a glass laser system capable of providing high energy, spike-free output in square pulses of 1, 3, 10, 30 and 100 microsecond lengths. Output beams spread was on the order of 2 mrad or less. A general description of the laser system and its operation is presented first. Each of the major system sections (Laser Generator, Laser Preamplifier and Final Amplifier) are described in detail. Finally, typical output waveforms are shown.

FOREWORD

This report was prepared by the Central Research Laboratory, American Optical Corporation, Southbridge, Massachusetts under Contract N00014-66-C-0056 entitled INTERMEDIATE PULSEWIDTH LASER SYSTEM. The work was performed under the direction of the Office of Naval Research.

The work reported herein began 1 August 1965 and was concluded on 30 December 1970. Dr. C. G. Young was responsible for overall project management at the Research Laboratory. J. W. Kantorski was project scientist.

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FINAL TECHNICAL REPORT

INTERMEDIATE PULSEWIDTH LASER SYSTEM

1. INTRODUCTION

The purpose of this program was to design and construct a glass laser system capable of providing high energy spike-free output in square pulses of 1, 3, 10, 30 and 100 microsecond lengths. The output beams spread was to be two milliradians or less.

The contract work was split into two phases. Phase One was to study feasibility of such a system and was reported in Semiannual Technical Report No. 1 dated June, 1966. Phase Two was to design, construct and deliver a system based on the findings in Phase One.

The principle of operation is to provide amplified spontaneous emission with a generator rod or rods. This emission is smooth in output, i.e., spike-free, and typically under high-gain conditions, has a duration of 250-300 microseconds full width at half height. At the peak generator output, Kerr cells are switched to provide a square pulse of amplified spontaneous emission. The Kerr cell output is then fed into a preamplifier to further increase signal intensity to drive the final amplifiers. The total output from the combined final amplifiers is to be 1000 joules. If pulse sharpening occurs, the ramp generator can be employed to offset this pulse deformation and provide a square wave output pulse.

The system beams spread is controlled by the overall length of the system and the use of afocal telescopes. The diameter of the final amplifier divided by the overall length of the system is the aspect ratio. This determines the minimum beam divergence that can be obtained without the use of afocal telescopes. Because the rods used in the generator section have

a smaller diameter than the preamplifier, an afocal telescope was used to expand the beam from the generator to match the preamplifier cross section. This reduction of beam divergence also helps to overcome a degradation of beams spread due to thermal distortion in the preamplifier. A second afocal telescope used between the preamplifier and the final amplifiers is a help in further reduction of the beam divergence as well as providing an expanded beam diameter to match the cross section of the final amplifiers.

The energy storage in capacitor banks required to operate the complete device is in excess of 400,000 joules. This amount of energy storage was not available at the American Optical Corporation. By prior mutual agreement between ONR, AFWL and AO it was decided that initial tests would be done at AO using the 240 kJ available there. Later, it was also mutually agreed that when a reliable output of 100 joules was obtainable from the preamplifier, the system would be dismantled and shipped to Kirtland AFB to be used with the 600,000 joules of energy storage available there, in part because the KAFB supply is a 30 kV unit, and the AO supply operates at 5 kV. Technical representatives from AO would then assemble and align the system through the preamplifier stage and render any assistance deemed necessary to install the final amplifiers.

2. GENERAL DESCRIPTION OF THE LASER SYSTEM AND ITS OPERATION

In order to provide spike-free output pulses, a non-resonant laser system was built using five Nd-doped glass amplifiers aligned in series with two parallel final amplifiers. The amplifiers are optically disconnected from one another by electro-optic switches consisting of Kerr cells and Faraday rotators until each amplifier is at peak gain. At that time the Kerr cells are activated allowing the generation of a single pulse that is transmitted and amplified in the forward direction. The optical isolators prevent a build up of energy in the backward direction. Figure 1 is a schematic of the optical system as it was laid out on 54 feet of table length.

The system was designed to operate semi-automatically. The power supply to energize the flashlamps was first charged to the desired voltage; the operator then activates the system

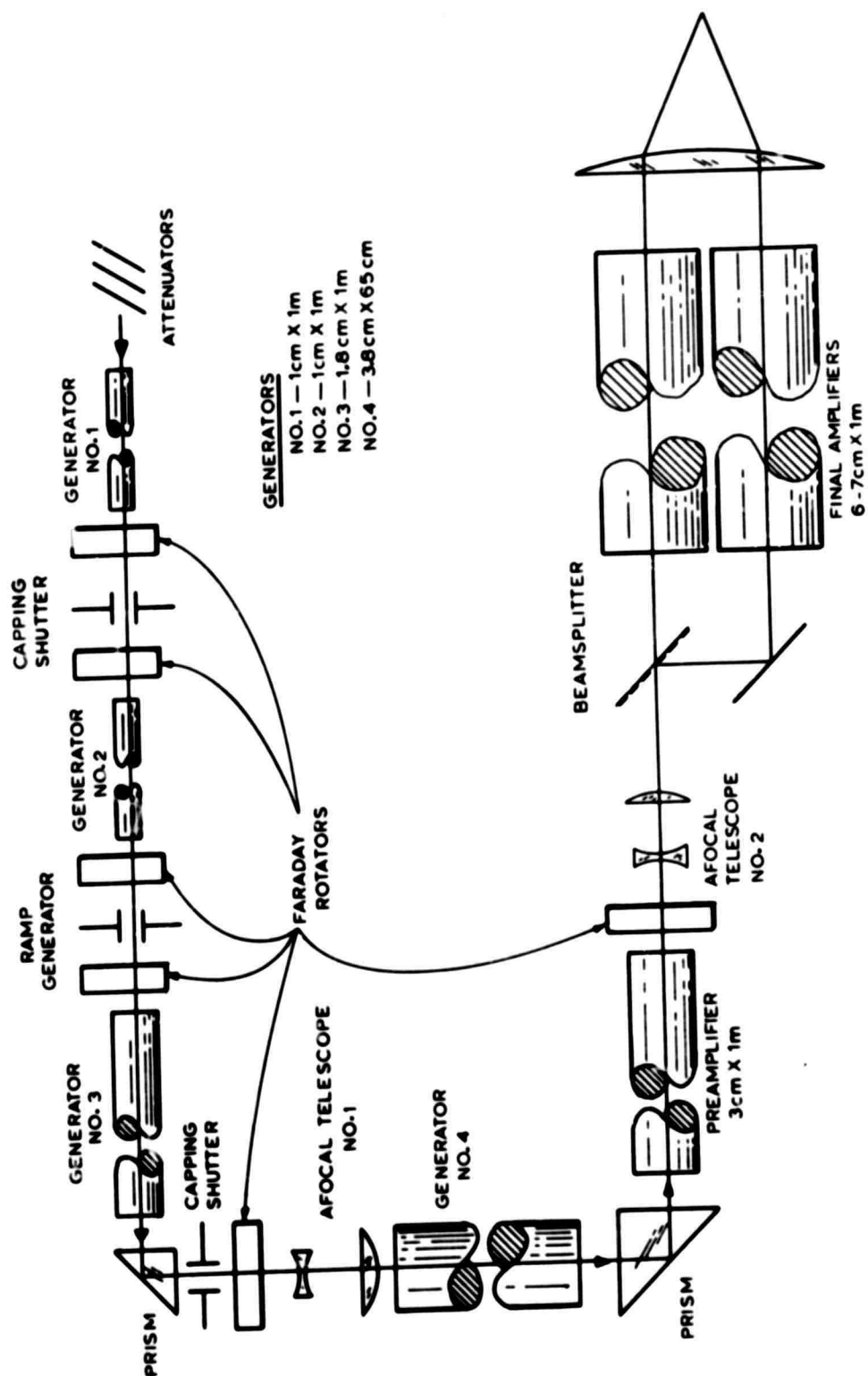


Figure 1. System design.

with one push button. A series of electronic delay units are coupled together to energize the electromagnets for the Faraday rotators and fire the flashlamps in proper sequence. After the flashlamps are fired, the Kerr cells are activated when the amplifier chain is at peak gain and finally, the electromagnets are deactivated.

For convenience in discussing the system and to split up the experimental work in phases, the first four amplifiers were designated the generator section. The prime function of this section was to generate a properly-shaped pulse of the desired time duration and sufficient energy to drive the preamplifier to an output of approximately 100 joules. The generator section is the high gain section of the device with 160 dB or more of gain available.

The requirement for high gain necessitates the use of some method to eliminate feedback that may be provided by specular or diffusely reflecting surfaces in the system. Furthermore, when the Kerr cell switches are activated, all the amplifiers are connected in series and there will be a flow of energy in the backward direction equal to the energy in the forward direction. This condition will cause depletion of the gain in the generator rods and limit the output energy if it is not prevented. Also, if at this time, unwanted reflections do occur, the system could become a high gain oscillator with disastrous consequences. The only practical method available to prevent this is to make use of optical isolators that allow radiant energy to be transmitted in the forward direction while attenuating any energy in the reverse direction. Faraday rotators perform this function. In order to make use of this type of optical isolator the 1.06 μm emission was linearly polarized. The requirement for a square output waveform of variable width required the use of electro-optic switches. Kerr cells were chosen that operate at 12-15 kV for half-wave retardation as the electro-optic modulators. Since the system made use of linearly polarized light, no additional polarizers were necessary for the operation of the Kerr cells. Three Kerr cells are used in the system as indicated in Figure 1. When the system is fired, the first Kerr cell acts as a capping shutter and produces a square pulse of the desired width that is further amplified by the second generator rod. The second Kerr cell is provided with an electronic driving circuit that produces a ramped transmission function. This is required in order to compensate for the gain depletion produced by saturation

in the preamplifier and final amplifiers. The third Kerr cell is a capping shutter driven in parallel with the first Kerr cell. Its main function is to decouple the third generator rod from the succeeding amplifiers and minimize the DC energy level in the final output.

The preamplifier section consists of a single glass amplifier and a large aperture Faraday rotator. The function of the preamplifier is to increase the signal level to about 100 joules output to drive the final amplifiers. The main purpose of the optical isolator in this section is to attenuate reflections produced by target feedback that are amplified by the final amplifiers.

The final amplifier section consists of two parallel large diameter (7.5 cm) amplifiers that can be aligned to direct the output energy through a condenser lens to a common focus.

3. LASER GENERATOR SECTION

3.1 GENERATOR RODS

The generator rods used in this section of the system must be capable of attaining very high gain with moderate pump input. Based on past experience, 1 centimeter diameter by 1 meter long glass laser rods with an 85 centimeter pumped length were chosen for use in the device.

Several generator rods were fabricated for evaluation. The first of these was from AO 3669B laser glass doped with 5 wt% Nd_2O_3 . It was a Brewster-ended rod with rough sides and was immersed in an aqueous solution of 10% NaNO_3 except for the ends. The rod was pumped with two flashlamps in a close-wrap configuration. Figure 2 is a plot of the small signal gain as a function of pump input with a one millisecond pump pulse duration. The maximum gain measured was 48 dB at a pump input of 15.4 kilojoules. Increasing the pump input beyond 15.4 kilojoules did not increase the gain and it was an indication that off-axis amplified spontaneous emission produced gain depletion. To test for this, the signal pass amplified spontaneous beamsread was measured and found to be 0.3 radians full angle, full energy. An angle as large as this could only be accounted for by total internal reflection (TIR) at the

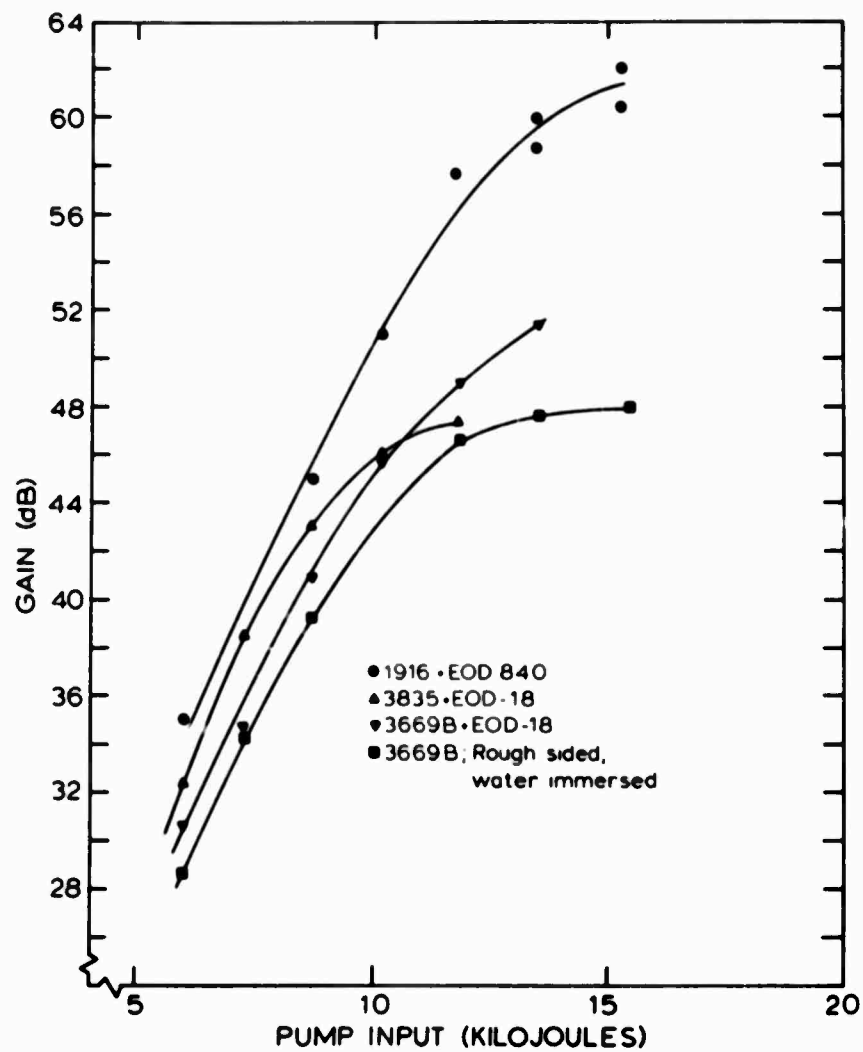


Figure 2. Small signal gain of four generator rods as a function of pump input. Pump duration 1916+EOD84, 2 ms; all others 1 ms. Pumped length 85 cm.

glass-to-water interface. This glass laser amplifier was therefore not suitable because of the relatively low gain and the lower than desired brightness which is a function of the angle over which the amplified spontaneous emission is emitted.

In order to increase the TIR angle, and thereby reduce the number of total reflections possible within the laser rod, a 1 cm by 1 m rod of AO 3835 laser glass (also 5 wt% Nd_2O_3) was clad with a samarium-doped cladding (EOD-18). The overall diameter with cladding was then 15 mm. The cladding is thermally matched to the laser glass core, transmits the pump light and absorbs at 1.06 μm . The index of refraction of the cladding was lower than that of the core by 1 part in 800. The small signal gain as a function of pump input is also plotted in Figure 2. A maximum small signal gain of 48 dB was also obtained for this laser amplifier. Below the point of gain saturation, this rod exhibited higher gain as a function of pump input than the previous rod. The single pass amplified spontaneous emission beam divergence was measured and a considerable reduction was noted which was due to the use of the cladding glass. The beam divergence was decreased to 0.14 radians.

A third generator rod of AO 3669B laser glass was fabricated with absorbing cladding that had a higher index of refraction than the core glass by 1 part in 800, thus preventing TIR. The small signal gain curve is also plotted in Figure 2. A gain of 51.5 dB was measured at a pump input of 13.5 kilojoules and no serious saturation was evident. The extrapolated gain yielded 56 dB at a pump output of 20 kilojoules. The single pass amplified spontaneous beam divergence was reduced to 0.1 radians.

A fourth amplifier was fabricated of AO 1916 laser glass clad with samarium-doped glass with an index of refraction higher than the core by 1 part in 600. The doping concentration was reduced to 4 wt% Nd_2O_3 in order to obtain more uniform inversion as a function of radius in the core glass. Under these conditions, a gain of 61 dB (Figure 2) was obtained at a pump input of 15.4 kilojoules in 2.0 milliseconds. The single pass amplified spontaneous beam divergence was reduced to 0.08 radians. Thus, this method of construction yielded the highest gain with a reduced beam divergence.

The reduction in the single pass amplified spontaneous beam divergence is very important because of the length of the system and the vignette problems involved. Accordingly, with

this beam divergence the energy passing through an aperture in the system is increased by a factor of 16 for equal gain compared to the 3669 laser amplifier without cladding.

As a result of the preceding experiments, the first two generator rods were fabricated from the high gain AO 1916 laser glass with samarium cladding. The ends of the rods were finished at Brewster's angle. The pump cavity was of a close-wrap design utilizing two 1 m long flashlamps 24 mm in diameter operated with a 2 ms pump pulse for long flashlamp life.

The third generator rod was fabricated from AO C2338 glass 18 mm in diameter by 1 m long, Brewster ended and doped with 2 wt% Nd_2O_3 to obtain uniform pumping. The rod was liquid cooled with an aqueous solution of 10% NaNO_3 . The necessity for using a rod of this type for the third generator rod was dictated by experiments performed using three generator rods of AO 1916 glass. To provide the required energy of 12-16 joules output in one microsecond at the output end of the first three generator rods required an energy density of 15-20 joules/cm². When the system was fired and the required energy was obtained, there was some internal damage to the third generator rod which had been manufactured in a low platinum environment. A glass made in an all-ceramic environment similar to the AO 1916 glass could have been developed but time was an important consideration. Also, a new cladding glass would have to be designed to match the thermal characteristics of the new core glass. The whole process can be a very involved and time consuming. Since a surplus of gain was available from the first three generator rods, it was decided to use the AO C2338 laser glass with a diameter of 18 mm. The maximum small signal gain was 30 dB (Figure 3), with a pump input of 24 kilojoules and was sufficient. By using a larger diameter rod the beam diameter at the exit end was increased to 15 mm and therefore the energy density was reduced by a factor of 2.25.

Another consideration for using an unclad laser amplifier for the third generator rod has to do with the propagation of linearly polarized light through glass. In general, if a laser amplifier is clad with glass and the thermal properties of the cladding do not match those of the core glass exactly, there can be some residual stress birefringence left in the core glass even after proper annealing. As a result linearly polarized light injected at the input end of the amplifier can become depolarized. The degree of depolarization can be measured with

an analyzer at the output end. Only a qualitative examination was made on a clad generator rod and it was decided that an excessive degree of depolarization was present.

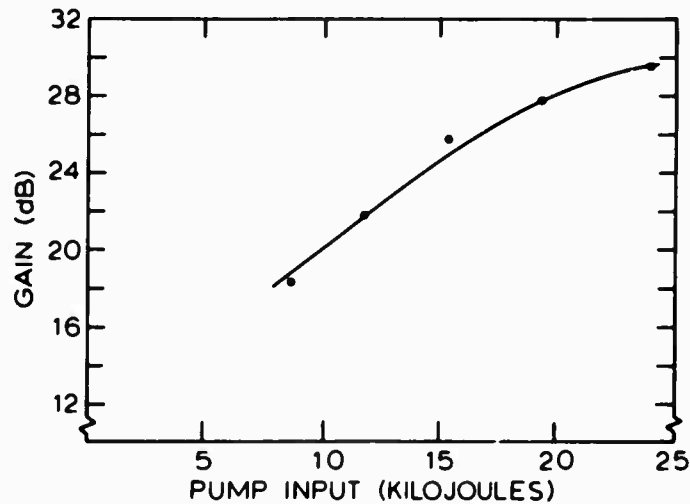


Figure 3. Small signal gain of AO C2338 laser glass as a function of pump input. Pump duration, 2 ms; pumped length, 85 cm.

Depolarization effects produced by the unclad third generator rod were measured for the pumped and unpumped cases. The $1.06 \mu\text{m}$ signal into the third generator rod is linearly polarized by virtue of having passed through a Faraday rotator with a Glan type double beamsplitting polarizer at the output end. The polarization vector was in the low-loss plane for the Brewster ended rod. The throughput was analyzed with another calcite polarizer and the signal was monitored with a photo-detector. Measurements were made with the analyzer parallel to and then perpendicular to the low loss plane for both the pumped and unpumped cases. When the rod was unpumped the ratio of the signals was 20.8 dB and when pumped it was 10.65 dB. Thus approximately one percent of the signal was in the undesired plane of polarization.

The fourth generator rod was 3.8 cm by 65 cm and was doped with 1.1 wt% Nd_2O_3 . The doping concentration was determined from data on uniformity of inversion versus rod

diameter that was obtained in other work at AO. A 3 cm cross section to match the preamplifier was actually used. The small signal gain measurements are presented in Figure 4. The use of a large diameter rod in this stage of the generator section permitted appreciable energy to be obtained with a minimal degree of pulse sharpening due to gain depletion. Energy outputs of over 20 joules in 1 microsecond could be obtained with approximately 1 dB of pulse sharpening.

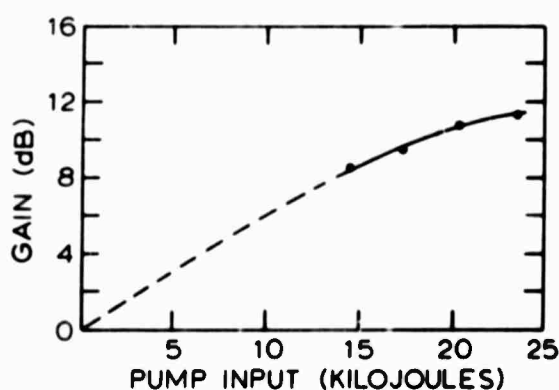


Figure 4. Small signal gain of 3.8 cm x 65 cm generator rod number 4 as a function of pump input. Pump duration, 1.2 ms; pumped length, 45 cm.

3.2 FARADAY ROTATION OPTICAL ISOLATORS

In order to achieve stability and high gain in a multi-stage laser amplifier system, it is necessary to have amplifier sections optically disconnected until the desired moment of signal passage. As soon as the amplifier sections are connected, provision must be made so that a signal can travel only in the desired direction through a system. The first function can be provided by mechanical choppers, Kerr cells, bleachable filters, rotating mirrors or other devices. But, unless the system is transit-time limited, no isolation is provided during the pulse; this system is therefore not considered further here. The only presently practical method for providing the second function, a "one-way valve" for radiation, is to employ a Faraday rotation optical isolator.

Since 1845, it has been known that when a block of glass is subjected to a strong magnetic field it becomes optically active. When plane-polarized light is sent through glass in a strong magnetic field, the plane of polarization is rotated by an amount θ where

$$\theta = V H l. \quad (1)$$

In this equation, the light has traveled a distance l through a material in which H is the component of the magnetic field in the propagation direction. The proportionality constant V , called the Verdet constant, is a function of the material used and the wavelength of light involved. In a Faraday rotation optical isolator, a glass sample in a solenoid is placed between a polarizer and an analyzer oriented at an angle of 45° to each other. A 45° rotation in the glass rod allows the forward-directed energy to pass through the analyzer polarized in the low loss plane. Energy traveling in the reverse direction encounters a 45° rotation in the same sense and is attenuated as it emerges polarized in the high loss plane of the polarizer. In practice, a high forward to backward ratio (F/B) is desirable, consistent with a low insertion loss.

Among the factors which limit the performance of an optical isolator are inhomogeneity of the magnetic field component along the optical path, residual stress-optic birefringence in the glass sample, reflection and absorption losses, and particularly in high energy systems, durability.

In general, the usual diamagnetic isolator glasses exhibit a Verdet constant that is considerably lower at $1.06 \mu\text{m}$ than in the visible portion of the spectrum. However, a terbium-doped paramagnetic glass has been developed at the American Optical Corporation. This glass exhibits a higher Verdet constant than most other isolator glasses at room temperature. In addition, its paramagnetic character results in an inverse functional dependence of Verdet constant on temperature. Thus, cooling to liquid nitrogen temperature (77°K) serves to increase V by about a factor of 4.

3.2.1 Optical Isolator Materials

A number of isolator glasses, suitable for use at $1.06\ \mu\text{m}$ are listed below. The data were obtained at room temperature unless otherwise noted.

Good optical quality Schott SF-6 is inexpensive and easily annealed to better than -30 dB residual stress-optic birefringence. That is, when placed between a pair of polarizers which in themselves exhibit a passive extinction ratio (parallel transmission/crossed transmission) greater than 50 dB, the extinction ratio becomes 30 dB. Although SF-6 has the lowest absorption at $1.06\ \mu\text{m}$ of all the candidates, its low Verdet constant requires a long sample, thus spatially increasing the demands on magnetic field homogeneity.

TABLE 1

Glass	$V_{1.06\ \mu\text{m}}$ (Min. gauss $^{-1}$ cm $^{-1}$)	Absorption at $1.06\ \mu\text{m}$ (cm $^{-1}$)	Length for 45 Rotation (cm) H = 6000 gauss
Schott SF-6	0.02	~ 0.0008	23
Schott SFS-6	0.03	~ 0.007	15
Corning 8463	---*	~ 0.003	--
AO Arsenic Trisulfide As $_2$ S $_3$	0.08	~ 0.030	5.6
AO Terbium Glass	0.08	~ 0.008	5.6
Liquid Nitrogen Temperature	0.30	~ 0.008	1.5

*Not measured at $1.06\ \mu\text{m}$, but was 0.09 min. gauss $^{-1}$ cm $^{-1}$ at 6328 Å; approximately the same as Schott SFS-6.

Schott SFS-6, although it has a somewhat higher Verdet constant than SF-6, is not the best choice of isolator material for four reasons. It is expensive and difficult to anneal adequately; all pieces received exhibited visible striae; its relatively low Verdet constant makes necessary a rather long sample. To a lesser degree, the same remarks apply to Corning 8463.

The high Verdet constant and low cost at once makes As_2S_3 glass attractive as an isolator material at $1.06\text{ }\mu\text{m}$. Although the glass is a very dark red to the eye, an incandescent lamp filament can easily be seen through about 60 mm of it so that visual system alignment is possible. Also, its good transmission in the near infrared allows the use of infrared converters to ease alignment problems. The high refractive index of As_2S_3 at $1.06\text{ }\mu\text{m}$ results in a 17% Fresnel loss at each air-glass interface. This can be reduced to a few tenths of a percent by applying a monolayer of thorium oxy-fluoride. However, poor thermal properties and high bulk absorption loss must still be tolerated thus reducing its desirability as an optical isolator material. The As_2S_3 glass is capable of withstanding 30 J/cm^2 of $1.06\text{ }\mu\text{m}$ laser energy in a 1.4 ms pulse.

The AO-terbium-doped glass is the most appealing of the rotator glasses at $1.06\text{ }\mu\text{m}$. It has a high Verdet constant at room temperature along with a fairly low absorption. Its transmission through the visible portion of the spectrum is about 99%, and it can be annealed to a state of low stress optic birefringence. Also, since for this glass V increases with decreasing temperature, very short samples (or very low magnetic fields) could be employed at, say, liquid nitrogen temperature.

3.2.2 Optical Isolator Magnets

In addition to being reasonable in size, weight, power consumption and cooling requirements, a Faraday rotation magnet requires a uniform axial magnetic field for producing the rotation. This field must be spatially (particularly in the radial direction) and temporally uniform to within 3% in order to achieve 30 dB of isolation.

Such a field may be obtained with a long solenoid, but more compact units have been fabricated by either attaching extra coils at the ends of a shorter solenoid, with a higher

current density than the central solenoid, or using a notched ID solenoid design such as was obtained from the National Magnet Laboratory at Massachusetts Institute of Technology. The latter approach allows the accurate calculation of the dimensions and uniformity of the field. Coils of both types were constructed and studied with a Hall probe Gaussmeter and were utilized for preliminary measurements before the magnets discussed below were available.

A somewhat better, commercially available approach is to wind the solenoid with thin, electrically insulated aluminum foil and then machine out a notch in the inside diameter to obtain the desired field homogeneity. A 2.54 cm diameter bore, 15 cm long electromagnet was purchased from the Ogallala Electronics Co., Ogallala, Nebraska. The solenoid was fabricated from high purity aluminum foil (cryalum) interleaved between a dielectric material. High grade aluminum was chosen as its electrical resistance decreases by a factor of 12 at liquid nitrogen temperatures. Thus, along with the advantage of less weight and overall size, power consumption decreases by a factor of 12 (60 amperes at 15 volts for 6000 gauss) and heat generation becomes minimal.

As received, the solenoid was built into an insulating cabinet to contain the liquid nitrogen. After filling the unit with liquid nitrogen (12 liters for cool-down plus fill) it was found that considerable icing occurred in the bore because of condensation. To remedy this problem, a nichrome wire-wound, thin wall brass tube was inserted into the axial bore to serve as a heating element. An electronic thermostatic temperature control was employed to maintain constant temperature in the bore to within $\pm 1^\circ$. Measurements conducted with a Hall probe Gaussmeter revealed that the solenoid was axially homogeneous to within $\pm 3\%$ in the central 64 mm inches for fields up to 10 kilogauss. Radial homogeneity in the 64 mm central portion was within $\pm 1\%$. A drawing of the cryalum magnet is included as Figure 5.

One other approach, a permanent magnet, which would eliminate power consumption and heat dissipation problems was investigated. An alnico magnet, beer-barrel shaped, was made by the Arnold Engineering Company. The 2.54 cm diameter bore, 14 cm long magnet was found to have a 7.6×2.54 cm central volume with an axial field of 1000 gauss, axially uniform to $\pm 3\%$ and radially uniform to $\pm 2\%$. This field is sufficient to produce a rotator employing the terbium-doped glass at

liquid nitrogen temperature. The manufacturer claims that much higher fields in a permanent magnet design are not possible, within the homogeneity and length requirements. A drawing of the permanent magnet and its container is shown in Figure 6.

3.2.3 Optical Isolator Experimental Results

The unavailability of a continuously variable constant-current DC power supply made it difficult to obtain exact 45° rotations in the samples during preliminary testing. Consequently, the current (directly proportional to field intensity) was adjusted so as to produce a near 45° rotation and active extinction ratios were determined by rotating the analyzer through the positions of minimum and maximum intensity. As a test for residual birefringence in the glass samples, passive extinction ratios were measured with no applied field. The ends of the samples to be evaluated were polished flat and parallel and were not anti-reflection coated. The data for the samples tested are presented in Table 2.

TABLE 2

Sample	$l \times d$ (cm)	θ (deg)	Passive Ext. Ratio (dB)	Active Ext. Ratio (dB)
AO Terbium Glass	3.6×1.5	53	29	29
Corning 8463	4.7×1.5	45	40	28

Due to the unavailability of a high stability continuous light source at $1.06 \mu\text{m}$, the measurements presented above were made at 6328 \AA using a helium-neon gas laser source. The apparent performance limit of 29 dB is probably due to power supply ripple ($\pm 5\%$).

Previous to acquiring the cryalum magnet, several samples of As_2S_3 glass were prepared with ends flat and parallel and low reflection coated at $1.06 \mu\text{m}$. Each sample was 1.8 cm

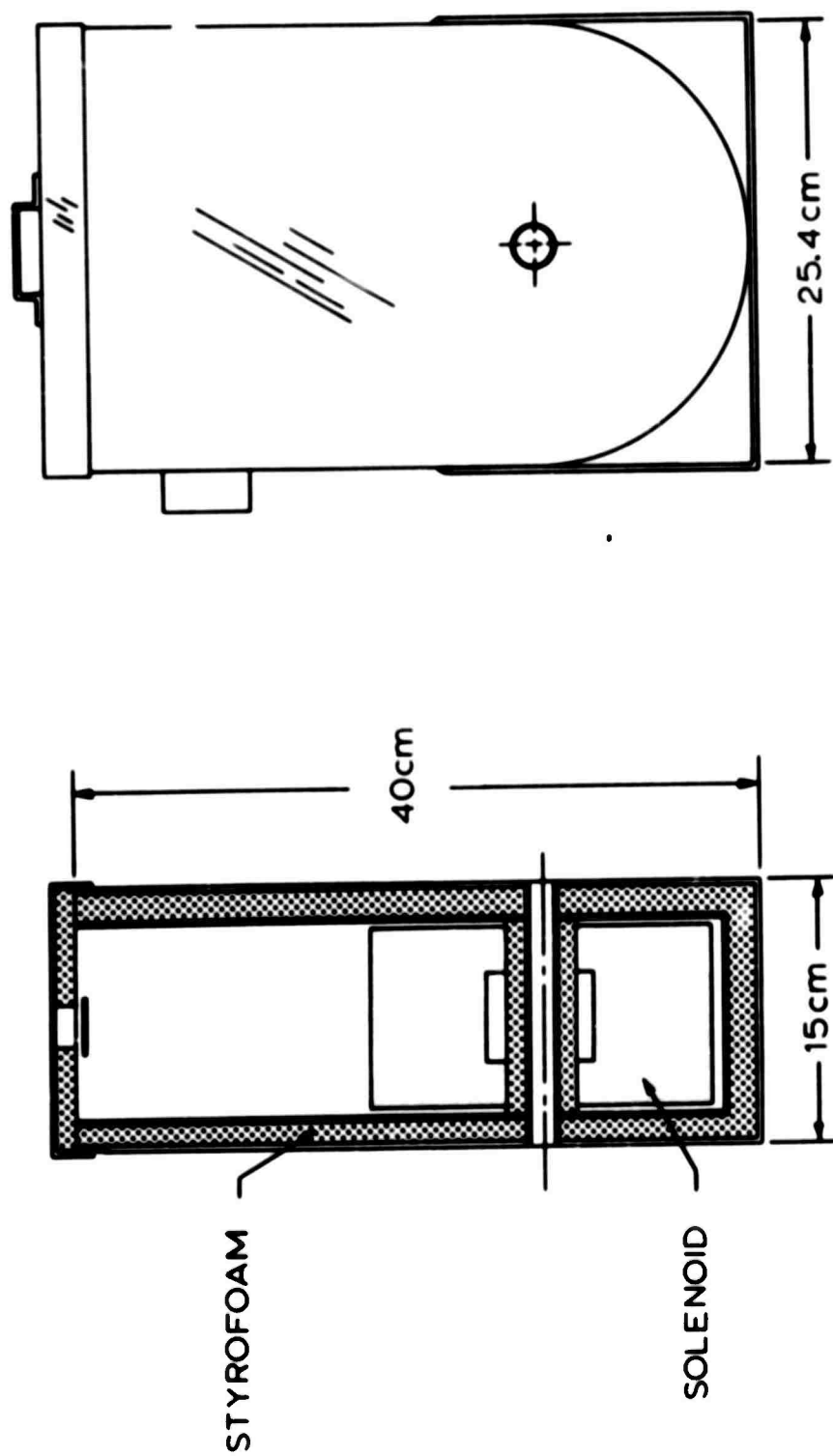


Figure 5. Cryalum foil-wound solenoid with notched center portion and styrofoam insulated container.

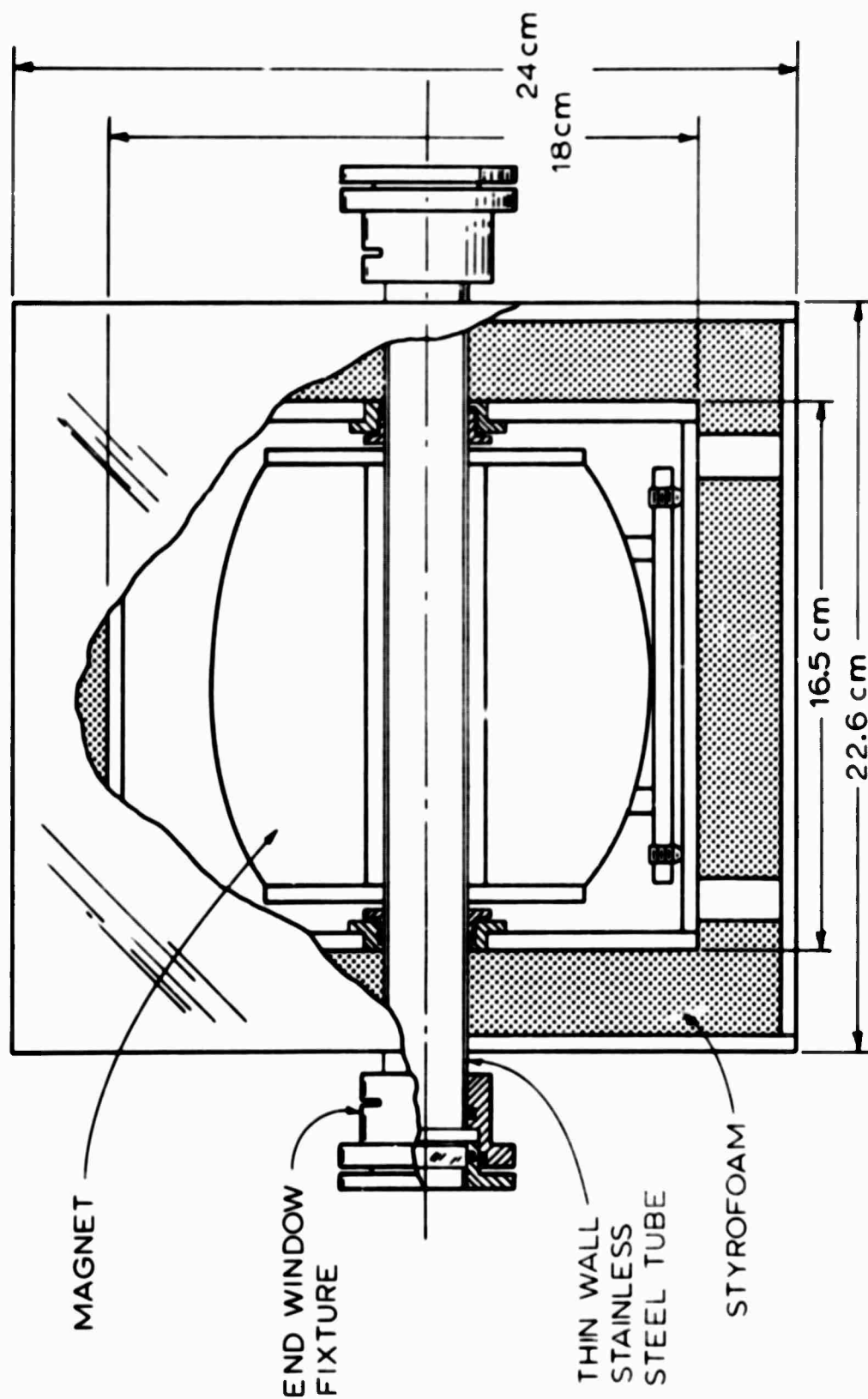


Figure 6. Permanent magnet and container.

in diameter and 7.0 cm long. These samples were evaluated at 1.06 μm using a 21.5 cm long copper wire-wound "spool shaped" electromagnet at room temperature. Table 3 lists the data for the samples tested. The ambiguity in the passive extinction ratios is due to the unavailability of a high stability, continuous 1.06 source.

TABLE 3

As ₂ S ₃ Sample Number	Passive Extinction Ratio at 1.06 μm (dB)	Active Extinction Ratio at 1.06 μm (dB)
2	≥ 27	21
4	≥ 28	24
5	≥ 26	19
6	≥ 28	20
7	≥ 26	18

A constant current (ripple < 0.1%) power supply was purchased from Eastern Scientific Instruments Corp. as a current source for the cryalum electromagnets. Although fields up to 10 kilogauss can be generated with this design, it was found that nitrogen boil-off due to increased heat generation becomes troublesome at the necessary high power inputs (94 amperes at 32 volts for 10 kilogauss). As a result, two 5.5 cm long \times 1.5 cm diameter glass samples were prepared which according to Eq. (1) require a field of 6.1 kilogauss to produce a 45° rotation. The ends of the samples, although flat and parallel, were cut and polished at a 2° angle to the long axis of each rod. Thus, direct feedback from the sample faces was eliminated.

Tests performed with a continuous, collimated beam from an incandescent source at 1.06 μm indicated a passive extinction ratio of about 27 dB for each sample. The unit was then evaluated using pulsed (250 μs), smooth amplified spontaneous output (1.06 μm) from a 100 cm long \times 1 cm diameter neodymium-glass laser rod. Directing the beam through each isolator in both the high and low loss directions resulted in a F/B ratio of 25 dB for each unit.

It should be pointed out that the samples appeared highly striated to the unaided eye whereas recent melts exhibit very little visible striae. With better optical quality and more finely annealed samples, F/B ratios of the order of 30 dB or greater can probably be expected.

In order to take advantage of the increased Verdet constant of terbium glass at liquid nitrogen temperatures, an insulating cabinet was fabricated to contain the 1000 gauss permanent magnet described above and an 8.2 cm long \times 1.6 cm diameter terbium glass sample was prepared. The optimum length of 8.2 cm was chosen as the homogeneous portion of the magnet. To eliminate direct feedback, the ends of the rod although flat and parallel were finished at a 2° angle to the long axis. For this sample, according to Eq. (1), a 40° rotation should result at $1.06 \mu\text{m}$ when operating at liquid nitrogen temperature.

The relative fraction of incident linearly polarized light transmitted by an analyzer is described by

$$I/I = \cos^2 \theta \quad (2)$$

where θ is the angle between the polarization direction of the incident beam and the low loss axis of the polarizer. By orienting the analyzer at an angle of 50° to the polarizer, maximum isolation is obtained at the expense of a fractional insertion loss which according to Eq. (2) amounts to $1 - \cos^2 10^\circ$ or 3%.

Measurements conducted with a continuous, collimated beam from a tungsten source revealed that the unit was capable of ≥ 25 dB of optical isolation at $1.06 \mu\text{m}$. The isolator was then tested using pulsed (250 μs), spike-free amplified spontaneous emission ($1.06 \mu\text{m}$) from a 100 cm long \times 1 cm diameter neodymium glass laser rod. By directing the beam through the unit in both the high and low loss directions, a F/B ratio of 26 dB was obtained.

Although permanent magnets are relatively cheap, perhaps their biggest disadvantage is that they are continuously operating so that for alignment purposes, the insertion of a retardation plate between the polarizers or the rotation or removal of one of these polarizers is necessary. In addition, windows are required to keep the sample from frosting. They may

cause troublesome reflections as well as increase the axial length of the unit. Also, due to the fixed magnetic field, operation over a range of wavelengths is not easily afforded. According to Eq. (1), either the length of the sample (l) or the temperature ($V \propto 1/T$) must be altered to achieve wavelength versatility.

3.2.4 Optical Isolator Polarizers

Commercial calcite air-spaced prisms are quite adequate for many isolator applications. The double beamsplitter type with all entrance and exit faces antireflection coated was considered best from a feedback-stability standpoint. At the time the system was designed, no data were available on the durability of calcite polarizers in the intermediate pulse domain. However, it was felt that in the generator portion of the system, the energy density would be low enough to utilize calcite for the polarizing medium. The calcite polarizers had a 12 mm square cross section and the extinction ratio for two crossed polarizers was in the neighborhood of -50 dB.

3.2.5 Final Design of Optical Isolators

The final design of the optical isolators in the generator section was based on the above experimental results. The cryalum electromagnet was chosen as the most convenient to use because it could be pulsed on only when needed and also because the losses due to reflecting surfaces were lower since no windows were needed at the ends of the magnet bore as opposed to the permanent magnet design. Furthermore, due to its shorter length, alignment of the magnet and the glass isolated element was simplified.

The rotator element is AO Terbium glass 5.5 cm long by 1.5 cm diameter finished with the ends parallel and tilted 5° with respect to the cylinder axis. A front to back ratio of > 28 dB was obtained. The total isolation provided by the 5 Faraday rotation elements in the generator section is therefore ≥ 140 dB.

3.3 ELECTRO-OPTICAL MODULATOR CONTROL OF THE AMPLIFIED SPONTANEOUS EMISSION

There are two separate problems involved in controlling the amplified spontaneous emission to provide a square output pulse from the final amplifiers. The first problem is to control the pulse duration. This can be done with a capping shutter consisting of a Kerr cell with associated electronic driving circuits. The second problem is to control the shape of the pulse in the event that pulse deformation occurs in the amplifier chain due to operation in the saturated gain region. In this case the trailing edge of the pulse has less gain and as a result is not amplified to the same extent as the leading edge. To make up for this deficiency, the amplified spontaneous emission from the generator section must be increased as a function of time.

An investigation into the quality of commercially-available Kerr cells was made and cells by Kappa Scientific Corp. were selected as the best for this system, i.e., the absorption of the cells at $1.06\text{ }\mu\text{m}$ was measured to be $\frac{1}{2}$ /cm path length and the conduction was found to be very low (typical resistance of cells $> 10^{13}$ ohms). It is felt that this performance is the result of using only hyper-purity nitrobenzene to fill the cells. This should also eliminate ionic drift effects, producing an extremely uniform electric field and thus result in a uniform, complete optical closure. After this investigation was made, Kappa Scientific announced a new liquid for use in the cells (Kerrmax 550) that has a Kerr constant such that at $1.06\text{ }\mu\text{m}$, only 60% of the voltage used with a nitrobenzene fill is required for complete "opening" of the cell's transmission. This liquid is reported to have a much lower resistivity, but in applications not requiring biased operation, cells filled with this liquid should exhibit performance equal to the nitrobenzene units. Cells filled with Kerrmax 550 were used in this device. The use of Kerr cells to properly perform the necessary modulation of the amplified spontaneous emission does not easily lend itself to methods of control that synthesize the driving function at a low electrical power level and then amplify to a high enough level to drive the cell. Investigation has established that linear amplifiers with the required bandwidth and power output are not commercially available. Although it might be possible for American Optical to develop such an amplifier it was felt that the difficulty of the undertaking would have resulted in an expensive, time-consuming program and therefore, this approach was not taken. American Optical Research Division has had

considerable experience with hydrogen thyatron switching circuitry and it appeared that use of this technique lends itself particularly well to this problem. The generation of the square voltage form required for the "capping" cell and the trapezoidal voltage form required for the "ramp" cell are somewhat separate problems and are therefore discussed separately below.

3.3.1 Square-Wave Generator for the Capping Shutters

Usually, square high-voltage pulses for driving Kerr cells are generated by using a combination of capacitors and inductors into a pulse forming network (PFN) or delay line that is charged and then switched to the cell by use of a hydrogen thyatron. Use of delay lines is not practical for pulse lengths greater than a microsecond, so that for this project only the PFN method could be used. This method of generation, however, has the disadvantages of (1) not allowing simple adjustment of pulse duration, (2) requiring very large expensive components for the longer pulse durations, (3) having a rise-time and fall-time that is relatively long and dependent upon the number of network sections, and (4) an output waveform which has some ripple superimposed. To overcome these problems another method of generation was developed. Referring to Figure 7, V1 and V2 are both hydrogen thyatrons. R1 has a relatively high resistance and is used to charge C1. C1 has a capacitance large enough so that the load (the Kerr cell shunted by the cathode resistance of V1) will not effectively drain charge enough to result in "droop" in the output square wave. In operation, the HV supply is energized and C1 charges. When operation is desired, an initiating pulse "triggers" V1 into conduction. With a rise-time limited only by the thyatron rise-time plus whatever lengthening incurred due to stray inductance of the leads to the Kerr cell, the voltage level at C1 is impressed across the load. The same initiating pulse is used to start a delay circuit. At the end of the delay time, V2 is "triggered" into conduction by the delay circuit thereby shorting the load effectively to ground and terminating the output pulse. V2 also discharges C1 until the anode voltage and current of V1 and V2 are such that they can no longer be in conduction. Using this system for generation of the square wave will eliminate all the objections listed for PFN method.

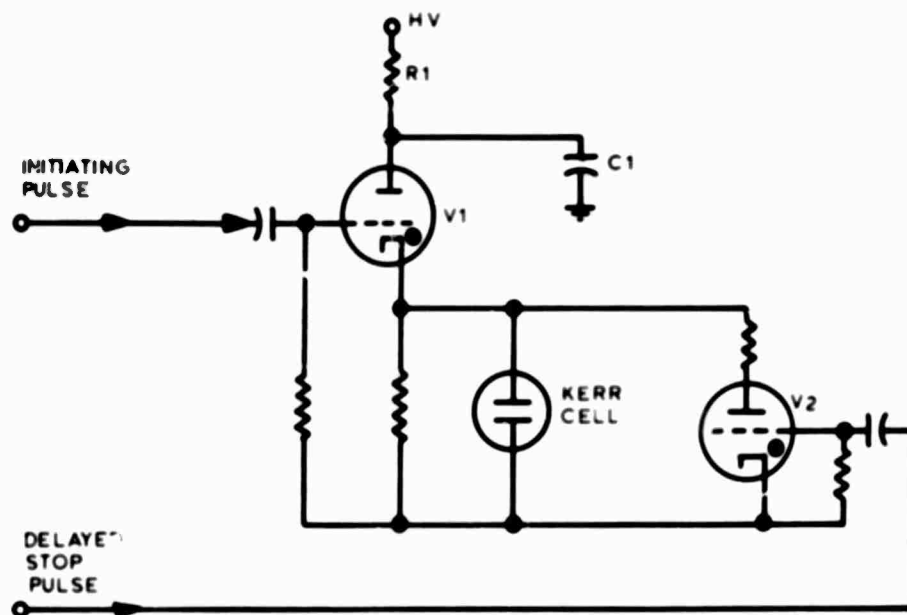


Figure 7. Schematic diagram of square wave generator circuit.

3.3.2 Trapezoidal Waveform Generator

The trapezoidal waveform generator drives the Kerr cell labeled ramp generator in Figure 1 and consists primarily of a square-wave generator similar to the one previously described and a linear ramp waveform generator which when added together form the voltage waveform needed to achieve the transmission function from the Kerr cell which is necessary to overcome pulse sharpening. Referring to Figure 8, the V1 and V2 stages form the square wave portion of the trapezoidal waveform generator and the V3 stage forms the ramp voltage waveform section. R1 is a high-ohmage, high-voltage resistor used to charge C1, while at the same time R3 charges up C2. On command an initiating pulse triggers V1 and V3 into conduction enabling (1) V1 to discharge C1 through R2 (Kerr cell being connected across R2) raising the voltage across R2 instantly to a level at which C1 was initially charged, (2) V3 to discharge C2 through L1 and R4 causing voltage across L1 to rise in a linear ramp fashion to the level at which C2 was initially charged - this voltage then being capacitively connected to R2 thus adding to the voltage already present at R2. A preselected delayed pulse is then fed

to V2 triggering it into conduction which decreases whatever voltage is present across R2 at that time rapidly to zero producing the desired waveform pulse.

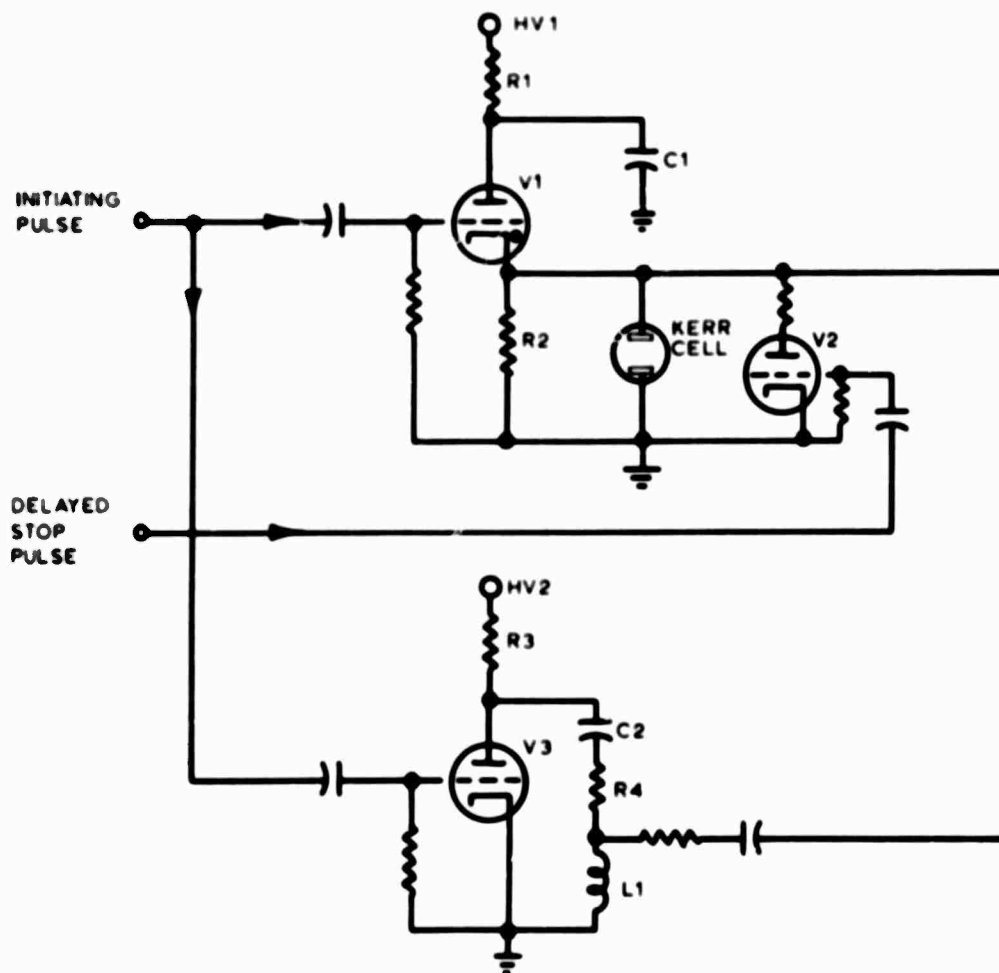


Figure 8. Trapezoidal waveform generator.

Voltage levels at C1 and C2 are variable enabling the voltage at the Kerr cell to not only change in amplitude but also in waveform - a very important feature which creates the fine adjustments the Kerr cell needs. A typical waveform is shown in Figure 9.

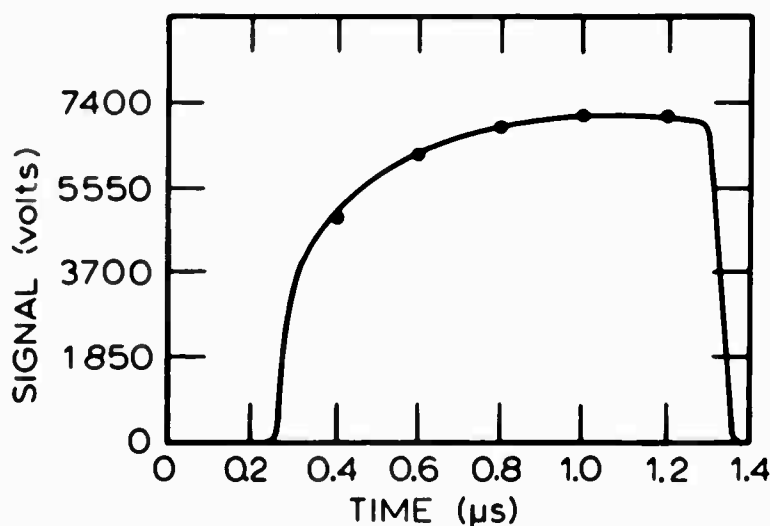


Figure 9. Typical waveform impressed across Kerr cell.

4. PREAMPLIFIER SECTION

The purpose of the preamplifier section is to deliver sufficient energy to drive the final amplifiers. The energy expected from the preamplifier is up to 100 joules or more and at that level problems of gain depletion can arise leading to pulse deformation for an initially square pulse. Included in this section is a large aperture Faraday rotator capable of allowing a 32 mm diameter beam to propagate through the glass element without vignette. The large aperture involved requires therefore larger aperture polarizers at the input and output ends of the Faraday rotator. At the time the system was designed, no information was available pertaining to the durability of calcite polarizers which were very expensive for the large aperture involved. It was felt that glass might be more durable and as a result stacked plate polarizers were designed and constructed for use in this optical isolator.

4.1 LASER PREAMPLIFIER RODS

The system was designed to produce a preamplifier output of 100 joules or more from a rod 3 cm in diameter and 1 meter long. The cross-sectional area of such a rod is 7 cm^2 and therefore the output energy density is approximately 14 J/cm^2 at an output of 100 joules. An energy density as high as this would produce pulse deformation in a Nd_2O_3 doped laser rod. However, the addition of Yb_2O_3 lowers the specific gain coefficient (β_g) as shown theoretically by Snitzer¹ and experimentally by data presented in Semiannual Technical Report No. 1. The experimental results placed an upper limit of 0.02 for β_g . Thus for 1 dB of pulse sharpening on an initially square pulse, about 50 joules per square centimeter are required.

A preamplifier using double doped laser glass was fabricated with a doping concentration of 2.5 wt% Nd_2O_3 and 4 wt% Yb_2O_3 . The rod was 1 meter long with a 3 cm core and clad with samarium glass which increased the overall diameter to 3.8 cm. This glass behaves somewhat like a three-level laser material in that unpumped regions exhibit a higher loss coefficient than do the pumped regions. Because of this, a laser rod fixture was designed to minimize the length of laser rod that is not pumped. In order to do this, entrance and exit windows have to be provided. The windows were made of low loss laser glass doped with Nd_2O_3 . The windows and laser rod were Brewster ended and mounted in the low loss plane for the linearly polarized laser emission from the generator section. Provisions were provided in the fixturing to permit rotational adjustments of the windows with respect to the laser rod and thus achieve parallelism between the rod ends and the windows.

It was not certain that a uniform inversion as a function of radius could be obtained with this doping concentration. An experiment was performed to measure the uniformity using the system in Figure 10. A fiber optic probe connected to a photomultiplier tube was scanned across the image plane to measure the relative gain as a function of position for a constant pump input. The results obtained from this data showed that the center of the rod was 30% under pumped. Relating this to typical gains obtainable it means that if the rod has 14 dB gain at the center, the gain at the periphery of the rod would be 20 dB.

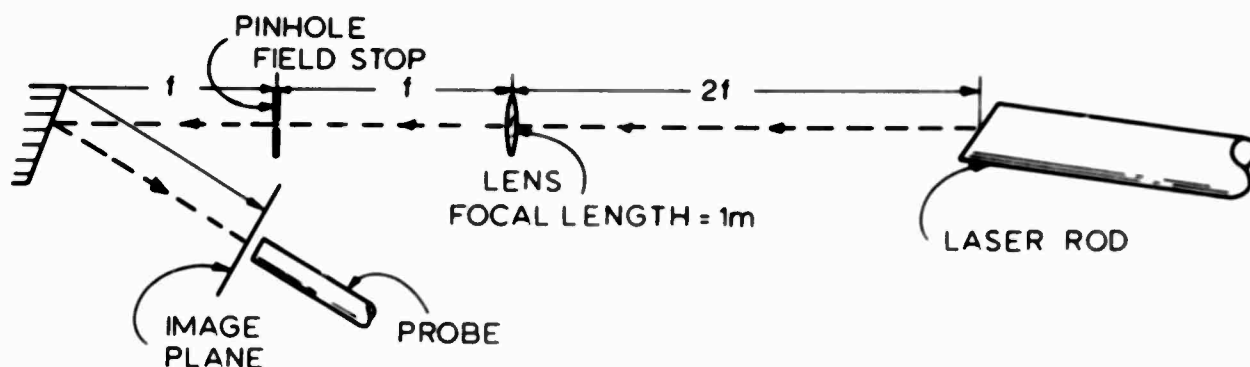


Figure 10. Schematic of system for study of pumping uniformity.

The non-uniform gain distribution has considerable bearing on the durability of the laser glass because in most cases one assumes an average energy density at the output end of a laser amplifier which is obtained by taking the ratio of the energy output to the cross-sectional area of the rod. If then the signal at the input end of the amplifier is of fairly uniform intensity, the intensity of the laser emission at the output end could be 4 times greater at the periphery of the rod than at the center using the gain quoted above. For this reason it was suspected that this preamplifier rod might damage.

The gain versus pump input for this rod was measured and is shown in Figure 11. The system was operated with a 1 micro-second pulse width. The preamplifier energy output was measured and at 47.6 joules output several damage sites occurred around the periphery of the rod at the output end and also in the output end window. The measurements on pump uniformity in the preamplifier suggested that the energy density was higher at the periphery of the rod resulting in the damage.

Due to the non-uniform pumping of the double-doped pre-amplifier with 2.5 wt% Nd_2O_3 and 4 wt% Yb_2O_3 it was decided to fabricate a new preamplifier rod with 2 wt% Nd_2O_3 and 3 wt% Yb_2O_3 . This was a compromise solution to obtain better pump uniformity and still have enough gain for the system to operate properly. Figure 11 is a plot of the small signal gain versus pump input.

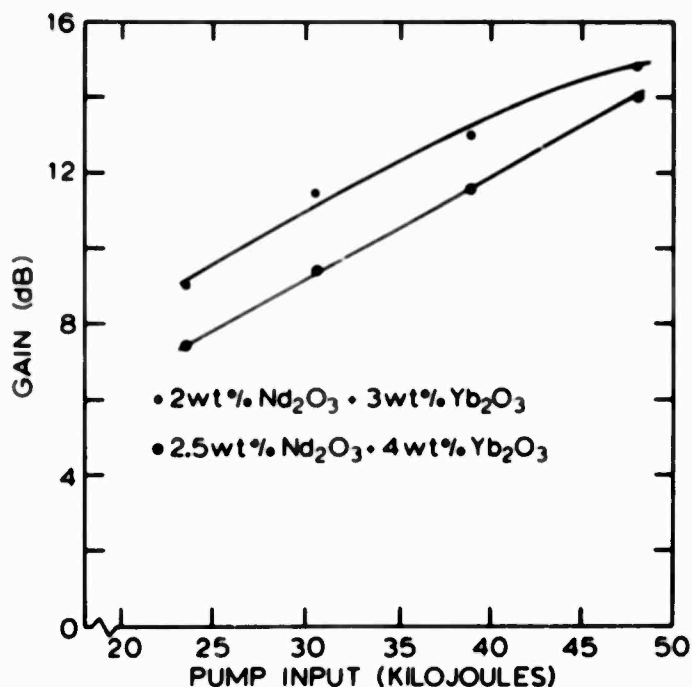


Figure 11. Small signal gain for 3 cm x 1 m double-doped preamplifier as a function of pump input. Pump duration, 2 ms; pumped length 85 cm.

The system was operated with a 1.5 microsecond pulse duration, and at an output level of 207 joules two damage sites occurred at the output end of the rod. Because the damage was very near the end of the preamplifier, the rod was shortened by cutting off the damaged portion and refinished. It was used in the system again and a damage site was produced near the edge of the rod at the output end at an energy output of 105 joules in 1 μ s. The input end of the preamplifier was then stopped down with an aperture stop to reduce the beam size from 3 cm to 2.7 cm thus preventing laser energy from impinging upon the damage site. After this was done, many shots were taken at energy output levels of between 90 and 101 joules with no further damage to the rod.

The damage that resulted in the preamplifier may have been due to excessive energy density along the surface of the rod due to non-uniform inversion. Time did not permit an investigation of the pump uniformity for this rod. As a result, it was decided to substitute for the double-doped preamplifier an unclad rod

3.8 cm in diameter and 1 meter long doped with 1.1 wt% Nd_2O_3 . The pump uniformity for this rod was known from other laboratory work and it was uniformly pumped over a 3 cm diameter and under pumped at the edges. The beam was restricted to 3 cm by an aperture stop at the input end.

Time did not permit firing the system with this rod. However, data from the personnel who used the system at Kirtland AFB showed that an output of 100 J in a 1 μs pulse was easily obtained without damage to the rod.

4.2 LARGE APERTURE FARADAY ROTATOR

The final optical isolator in the system was positioned after the output end of the preamplifier and due to its location it was necessary to provide an optical isolator capable of transmitting a large diameter beam without vignette. The output beam from the preamplifier was an ellipse approximately 3 cm \times 2.1 cm. Corning 8463 glass was chosen as the glass rotator element on the basis of optical quality, size available and Verdet constant which was approximately 0.03 at 1.06 μm .

The rotator element was nominally 13 cm long and 32 mm in diameter with the ends parallel and tilted 5° . It was necessary to antireflection coat the ends in order to get an active extinction ratio of 25 dB. Because of time consideration, it was necessary to fabricate the element in parallel with other elements used in the system. After the system was constructed to the point where it could be used to test the durability of optical elements in the 1 microsecond time domain, a sample of the glass was irradiated and found to damage at 10 J/cm² with a 1 microsecond pulse. The energy density in the rotator element was expected to range from 10 - 20 J/cm² and therefore the Corning glass was found to be unsuitable. No other suitable glass was available with as high a Verdet constant.

Experiments were conducted in the glass research laboratory at the AO Research Division to obtain a durable glass with sufficiently high Verdet constant. A glass with a Verdet constant of 0.038 at 1.06 μm was produced that withstood 80 J/cm² in a 1 microsecond pulse. A 11.4 cm long rotator element was fabricated for use in the device. A passive extinction ratio of 28 dB between crossed polarizers indicated the glass was sufficiently well annealed to be used for a Faraday rotator element.

Large aperture polarizers were also needed for the optical isolator and a choice existed between expensive calcite air-spaced prisms and stacked plate polarizers. Information was lacking on the durability of calcite for laser pulses in the microsecond time domain and accordingly, experiments were conducted to design a low loss stacked plate polarizer that would provide a Faraday rotator front to back ratio of ≥ 25 dB.

Initial experiments were done with a parallel plate stack of microscope slides at Brewster's angle and an extinction ratio of 18 dB was obtained at $1.06 \mu\text{m}$. This ratio was obtained by analyzing the transmitted beam with a calcite polarizer and measuring the signal in the high loss and low loss planes with a photomultiplier tube. The ratio of these two values is the extinction ratio.

In order to be useful for a large aperture optical isolator, a stacked plate polarizer having an extinction ratio of ≥ 25 dB is highly desirable. Due to the work of G. R. Bird and W. A. Schurcliff² an improvement on the design was obtained by using high index glass plates that are wedged and fanned. Twelve plates were fabricated of Schott SF-5 glass with an index of refraction of 1.73 at $1.06 \mu\text{m}$. Each plate had a 1° wedge angle. The first plate of the stack was positioned at Brewster's angle and succeeding plates were placed at slightly larger angles (called fanning) of 0.25° . Furthermore, since the stack consisted of twelve plates and it was highly desirable to minimize astigmatism, pairs of plates were used with the bases of the wedges opposed. With this arrangement an extinction ratio of 24 dB was obtained. The transmission of the assembly of plates was 0.965 for the low loss plane of polarization.

Based upon the above experiments a final version was evolved for the laser system. The design called for rectangular plates of high index glass (Schott SF-4) 37 mm wide by 62 mm long, with a 1° wedge angle and 10 mm thick at the base. Each polarizer consisted of 12 plates. The extinction ratio was measured to be 27.5 dB and the transmission in the low loss plane of polarization was 0.97.

5. FINAL AMPLIFIER SECTION

The final amplifier section consisted of two large diameter laser rods arranged to provide two parallel output beams that can be aligned to direct the output energy through a condenser lens to a common focus.

The original design of the final amplifier section called for use of 4 double-doped amplifier rods in parallel and clustered within the beam diameter provided by afocal telescope No. 2. The total cross-sectional area of the laser rods was 28 cm^2 and required an output energy density of about 35 J/cm^2 to provide a total output of 1000 joules. Due to the difficulty of manufacturing double doped laser glass of such high durability as mentioned above in the discussion of the preamplifier section, it was decided by mutual consent of personnel at ONR and AFWL and AO to provide two large-diameter laser amplifiers doped with 0.8 wt% Nd_2O_3 . The laser rods were approximately 7.5 cm in diameter and 1 meter long having a useful combined total cross-sectional area of 66 cm^2 . This meant that the energy density was reduced to 15 J/cm^2 at the output end of the system. With a preamplifier output of 50 joules, the gain required in each of the two final amplifiers would be in the range of 18 dB to obtain a final output of 1000 joules. Since gains of 13-14 dB have already been measured in amplifiers of this size at pump inputs of 80 kJ it was felt that this was a reasonable compromise.

Rods of this type were shipped to Kirtland AFB for installation by Kirtland personnel. Eight flashlamps are used to pump each of the final amplifiers. It was learned through conversations with personnel at Kirtland AFB that a gain of 12.3 dB was obtained in one of the final amplifiers at a pump input of 100 kJ in 1.4 ms. The KAFB power supply can put 200 kJ into each set of eight lamps.

6. TYPICAL OUTPUT WAVEFORMS

Spike-free output in square pulses of 1, 3, 10, 30 and 100 microseconds were obtained with the laser system. The original oscilloscope photographs were traced in order to provide high contrast reproductions for the report.

Figure 12a is an example of a typical one microsecond laser pulse obtained by driving Kerr-cell No. 2 with the high voltage square wave pulse in Figure 12b. The reduction in amplitude of the trailing edge of the laser pulse was due to gain depletion. To make up for the deficiency of gain at the trailing edge of the pulse the amplified spontaneous emission from the generator section must be increased as a function of time. By applying a ramped high voltage pulse to Kerr cell No. 2, the problem was overcome. Figure 13b shows the high voltage waveform impressed on the Kerr cell and Figure 13a is the resulting one microsecond laser pulse obtained.

Three microsecond pulses were obtained with waveforms as indicated in Figure 14.

Ten microsecond pulses were obtained by applying the high voltage ramp pulse in Figure 15b with the resulting laser output pulse in Figure 15a.

Figure 16a is an example of a 30 microsecond pulse obtained by impressing the high voltage ramped pulse in Figure 16b to Kerr cell No. 2.

Finally, a 100 microsecond laser pulse was obtained Figure 17a by applying the ramped high voltage pulse in Figure 17b.

Although specific pulse widths are illustrated in the above sequence, any pulse width desired between 1 and 100 microseconds can be obtained.

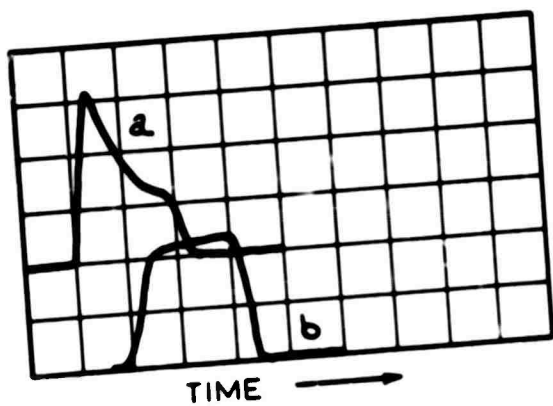


Figure 12. (a) Typical one microsecond pulse showing the effects of gain depletion. Scale $0.5 \mu\text{s}/\text{div}$. (b) High voltage pulse driving Kerr cell No. 2. (Ramp generator) Scale $0.5 \mu\text{s}/\text{div}$.

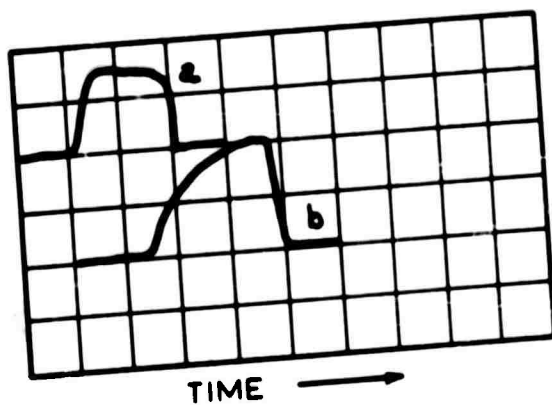


Figure 13. Correction for gain deficiency obtained by applying ramped high voltage pulse to Kerr cell. (a) one microsecond laser pulse. (b) High voltage waveform to drive Kerr cell. Scale $0.5 \mu\text{s}/\text{div}$.

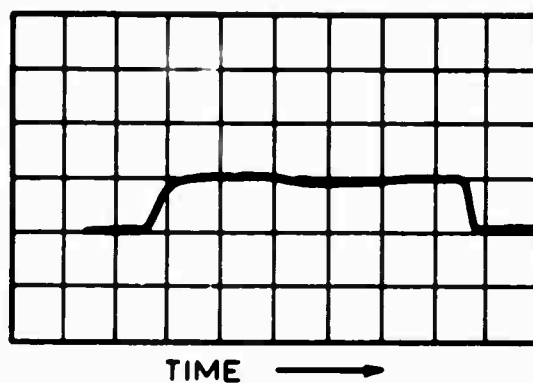


Figure 14. Typical three microsecond laser pulse.
Scale $0.5 \mu\text{s}/\text{div}$.

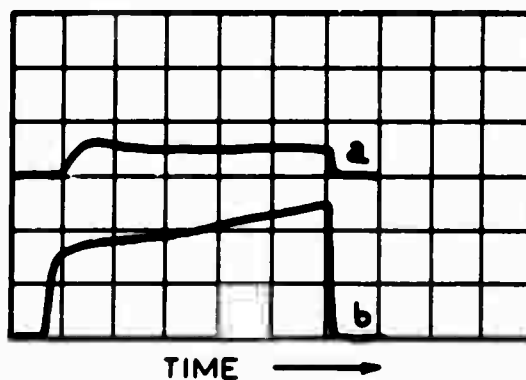


Figure 15. (a) Ten microsecond laser pulse. (b) High voltage waveform used to drive Kerr cell.
Scale $2 \mu\text{s}/\text{div}$.

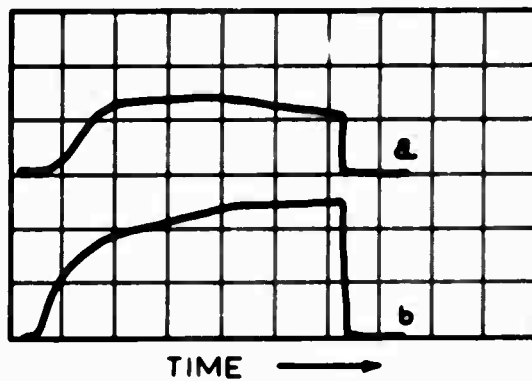


Figure 16. (a) 30 microsecond laser pulse. (b) High voltage ramp used to drive Kerr cell. Scale $5 \mu\text{s}/\text{div}$.

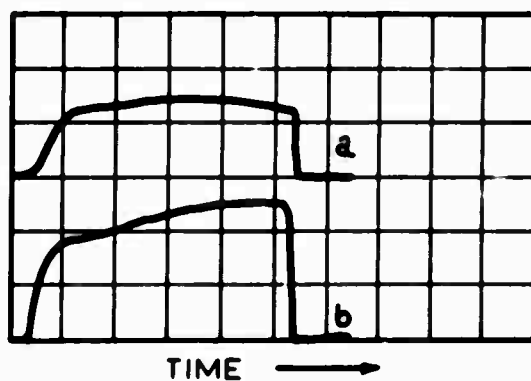


Figure 17. (a) 100 microsecond laser pulse. (b) High voltage ramp used to drive Kerr cell. Scale $20 \mu\text{s}/\text{div}$.

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